On the Ionisation of Gases by Collision and the Ionising Potential for Positive Ions and Negative Corpuscles.

By W. I. Pawlow.

(Communicated by Prof. Sir J. J. Thomson, O.M., F.R.S. Received March 11,—Read May 21, 1914.)

The object of the present research was to investigate the ionising properties of positive ions using a direct method, and to try experimentally to determine the minimum energy which is necessary for a positive ion to produce fresh ions by collision with a gas molecule. At the same time it appeared to be of interest to measure the ionising potential for negative corpuscles under experimental conditions somewhat different from those previously adopted.

§ 1. *Description of the Apparatus.*

The apparatus in the present investigation was used in two forms, represented in figs. 1 and 2. The part common to both forms consists of two

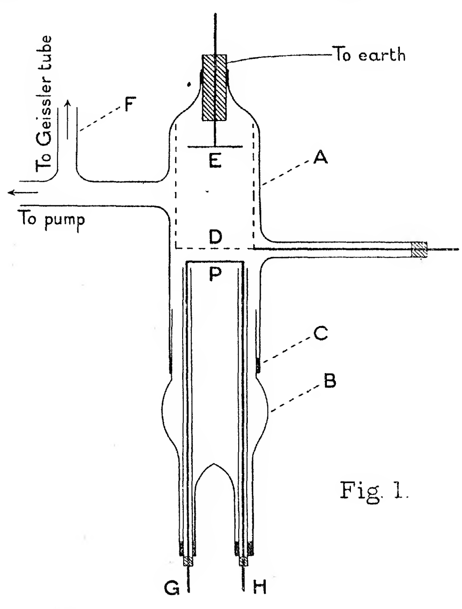


Fig. 1.

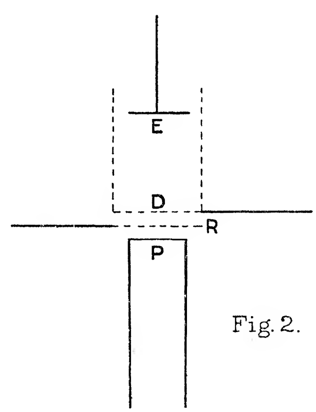


Fig. 2.

pieces of glass tubing, A and B—A, 3·5 cm. in diameter, B, a little less—the latter being blown out to a slightly spherical form, as shown in the diagram. The joint at C was made air-tight with sealing wax. By this means it was possible to take out the lower part very easily—a process which was very often necessary in order to renew the platinum strip P,

or to cover it with a fresh salt. In the narrow upper part of the tube A a brass rod was sealed with a round brass plate E at its end. This rod was insulated and surrounded by a brass tube connected to earth, to prevent it acquiring a charge from the glass. The plate E was used as an electrode to measure the ionisation, and was connected to a Wilson's tilted electroscope adjusted to a sensitiveness of 80 divisions per volt. The ionisation chamber was a wire-gauze cylinder D, through the open top of which passed the electrode E. The sides of the cylinder were made of brass gauze and the bottom of platinum gauze, which was fixed in clamps at the end of a brass rod which passed through a side tube and which held the cylinder in its proper position. The platinum strip P was of thin foil, 2 cm. long and 1 mm. wide. It could be heated electrically by means of the thick copper leads G and H, the current being supplied from a battery of six accumulator cells connected in parallel and regulated by wire resistances. The heating circuit was insulated. The copper leads G and H were covered with glass in order to make them more rigid and to keep them cool. These glass tubes and the leads themselves were sealed into two tubes joined to the spherical part of the lower tube. The tube B could be adjusted at the joint C, so as to fix the strip P at any distance from the bottom of the cylinder D.

The second form of apparatus differs only in having in the upper tube an additional side tube through which passes a brass rod holding a platinum gauze R, as shown diagrammatically in fig. 2. The gauze is parallel to the bottom of the cylinder, and is placed between the latter and the platinum strip P. The distance between the plate E and the gauze D in the different experiments was changed from 4 to 5 cm. The distances from D to R, and from R to P, varied from 1 to 2·5 mm. in different experiments. The wide tube connecting the apparatus to the gauge, pump, phosphorus pentoxide drying tube, and charcoal tube, was sealed into the upper part of the apparatus opposite the ionisation chamber. The platinum strip itself served as a source of negative corpuscles. In the experiments with positive ions the strip was covered with a layer of sodium phosphate, which was formed as usual by evaporating a water solution of the salt by gradually heating the strip. Sodium phosphate was chosen as a very intense* source of positive ions. In some of the first experiments aluminium phosphate was used.

§ 2. *Experimental Results.*

The method used in these experiments is originally due to Lenard† and was applied by him to the determination of the ionising potential for negative

* F. Horton, 'Roy. Soc. Proc.,' A, vol. 88, p. 138 (1913).

† P. Lenard, 'Ann. der Phys.' (4), vol. 8, p. 188 (1902).

corpuscles. This method was subsequently used by v. Baeyer,* Dember,† and Franck and Hertz‡ for the same purpose.

The experimental arrangements in the first form of apparatus were similar to those used by Franck and Hertz (*loc. cit.*), in their investigation of the ionising potential for the negative corpuscles, but in the present case, for the investigation of the positive ions, the potentials were of opposite sign. The platinum strip P was permanently charged to a negative potential V_1 volts, and the negative potential V_2 volts of the cylinder D was gradually altered, being always greater in its numerical value than V_1. The plate E was initially connected to earth, thus the electric force between the strip and the bottom of the cylinder was directed upwards, while the force inside the ionisation chamber was in the opposite direction. During the observations the earth connection of the plate E was broken, and the electric charge obtained by the plate was measured on the electroscope. In these conditions the positive ions emitted by the heated salt first went through the accelerating field of $(V_2 - V_1)$ volts, and entering the ionisation chamber were subjected to a still stronger retarding field of V_2 volts which prevented them from reaching the upper electrode E. The distance between P and D over which the accelerating field was applied was much smaller than the mean free path of the positive particles at the pressures used in the experiments. The distance between D and E over which the retarding field was applied was, on the contrary, much larger than the mean free path. One of the necessary conditions of the experiment is to communicate the energy to the positive ions during their free path. If the only source of the ionisation were the heated salt, emitting positive ions, the electroscope ought not to show any charge. If, however, the positive ions, after entering the ionisation chamber but before being stopped by the retarding field, came into collision with the molecules of the gas and ionised them, the negative corpuscles thus produced would be carried by the field V_2 to the electrode E and would thus communicate a negative charge to the electroscope. As a matter of fact, the electroscope showed a strong negative charge, confirming the presence of carriers of negative electricity in the gas under the action of the positive ions. By altering the value of the potential V_2 it was possible to investigate the change of the negative charge with the energy of the positive ions by which it was produced. In all subsequent values of the velocity of the charged particles, the fall of potential in the heated strip itself was taken into account. One end of it had a potential from 1 to 2 volts higher than the other end and in all results the

* O. v. Baeyer, 'Deutsch. Phys. Ges. Verh.,' vol. 10, p. 96 (1908).

† H. Dember, 'Ann. der Phys.' (4), vol. 30, p. 137 (1909).

‡ J. Franck and G. Hertz, 'Deutsch. Phys. Ges. Verh.,' vol. 15, p. 34 (1913).

velocity given corresponds to the higher value of the accelerating field. As an illustration of the type of curves obtained, the values for H_2, O_2, N_2 observed at the pressure 0·008 mm. are plotted in fig. 3. The actual numbers were reduced to the same scale so as to start from the same value of the ionisation at the point corresponding to the largest velocity used. The curves are all of similar form and approach the axis of x asymptotically. On the

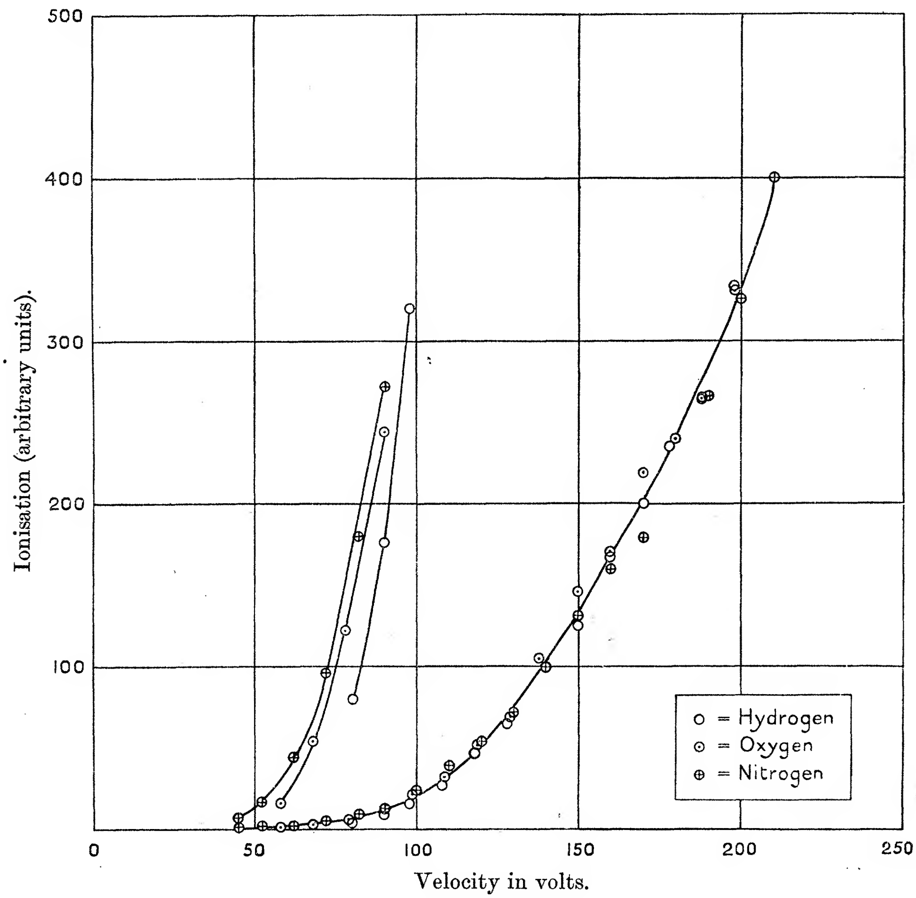


FIG. 3.

same fig. 3 the beginnings of the curves are plotted on a larger scale, showing that the curves for O_2 and N_2 seem to go down a little less steeply than H_2 curve. It was of special interest to try to find the point at which these curves cut the axis of x. For this purpose the intensity of the source of the positive ions was increased by making the platinum strip wider, coating it with fresh salt and heating it very strongly. In this way it was possible to continue the curves to the x-axis. Fig. 4 gives an example of the

results obtained with hydrogen for three values of the heating current—(1) 3·85 ampères, (2) 3·7 ampères, (3) 3·5 ampères. It clearly shows that the beginning of the curves actually depends upon the intensity of the

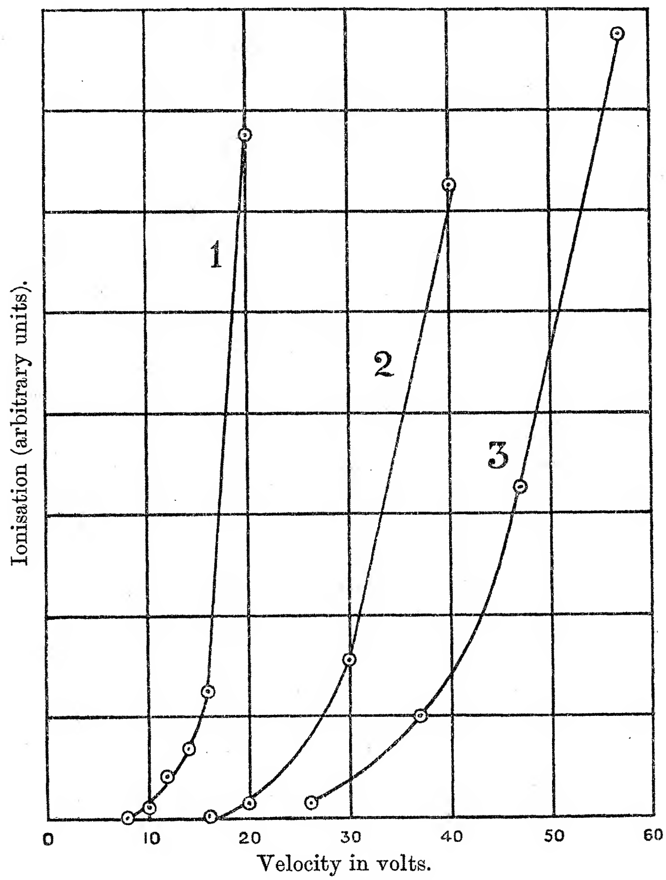


Fig. 4.

source of the positive ions and that it occurs in any case at a velocity lower than 10 volts.

One objection to the experimental arrangement here described is that as the field accelerating the ions changed, the number of the emitted particles no doubt changed also,* and therefore the asymptotic form of the curves might be due as much to the decrease in the number of the ionising agents themselves as to the decrease in the ionising power of the positive ions with the decrease of their velocity. In fact special measurements

* O. W. Richardson, 'Phil. Trans.,' A, vol. 207, p. 40 (1906); F. Horton, 'Roy. Soc. Proc.,' A, vol. 88, pp. 121, 127, 133 (1913).

have shown that, even at these low pressures (0·0005 mm.) and small distances (1 mm.), the thermionic current from platinum coated with sodium phosphate does not show complete saturation; the first branch of the curve passes gradually into the second, which rises less steeply with the voltage. In order to diminish this change in the number of positive ions themselves, and have a more constant supply of them which would not depend so much upon the accelerating field, slight alterations were made in the form of apparatus and in the method of observation.

The alteration is shown in fig. 2. It consisted in introducing the platinum gauze R between the source of ions and the bottom of the ionisation chamber. Throughout the experiment it had a small constant difference of potential with regard to the platinum strip P, and the accelerating force which was changed in the course of the observations was applied between the gauzes R and D. This small constant difference of potential between the strip P and the gauze R might be called, for brevity, "extracting" potential, to distinguish it from the difference of potential between R and D as "accelerating." The total energy acquired by a particle is, of course, equal to the sum of both the "extracting" and the "accelerating" potential. There is no doubt that any change in the "accelerating" potential would still have a slight effect upon the number of ions extracted from the strip P, but it is in any case much less than in the first form of apparatus.

The results of the experiments performed with this arrangement confirmed those which had been already obtained. The ionisation curves still preserve their characteristic shape, having the axis of x as asymptote.

In the course of the previous experiments the negative potential of the ionisation chamber was gradually altered through the whole interval of voltage investigated. With this arrangement the possible existence of negative corpuscles inside the ionisation chamber due to any extraneous causes must be considered. If the actual ionisation inside the cylinder does not depend altogether upon the velocity of the positive ions, but is partly due, for instance, to some radiation emitted by the glass sides of the vessel under the impact of positive ions, or to some negative corpuscles which, for any reason, penetrate into the ionisation chamber, or to the dissociation of heated salt vapour, the curves obtained would still be of the same general type. To avoid an error due to this possibility the following method of observation was adopted:—The ionisation chamber, *i.e.* the cylinder D, was kept at the constant potential of -207 volts during the whole time of observation. Only the potentials of the gauze R and the strip P were changed, the difference between the two being kept fixed, for instance, at 20 volts—the "extracting" potential. Under these

conditions the only variable was the velocity of the positive ions between R and D. The following table gives an idea of an actual series of observations and shows that any effects due to such extraneous causes as have been indicated would be too small to have any influence on the observations.

Potential of the strip P.	Potential of the gauze R.	Potential of the cylinder D.	Velocity of ions in volts.	Ionisation current in arbitrary units.
− 90	−110	−207	117	360
−100	−120	−207	107	230
−110	−130	−207	97	143
−120	−140	−207	87	93
−130	−150	−207	77	61
−140	−160	−207	67	29·5
−150	−170	−207	57	12
−160	−180	−207	47	5
−170	−190	−207	37	1·4
−180	−200	−207	27	0·5

§ 3. *Comparison of the Ionisation by Positive Ions and Negative Corpuscles.*

The scheme described above was finally adopted for two purposes: first, to compare the ionising action of positive and negative carriers of electricity emitted by hot salts and by heated platinum; secondly, to measure the ionising potential for the negative corpuscles under conditions somewhat different from those used by Franck and Hertz.* These experimenters found that the ionising potentials for H_2 and He are considerably different. These gases were therefore used in the following research. The hydrogen was prepared electrolytically and the helium by boiling powdered thorianite in nitric acid. It was carefully purified from possible impurities by passing it through tubes filled with charcoal and immersed in liquid air. During the whole experiment the apparatus was kept connected with the same charcoal tube. In order to be quite sure of the purity of the gas filling the apparatus at such low pressures, a small Geissler tube was placed in connection with it. The side tube F (fig. 1) led to a large glass vessel S, of which the narrow upper part

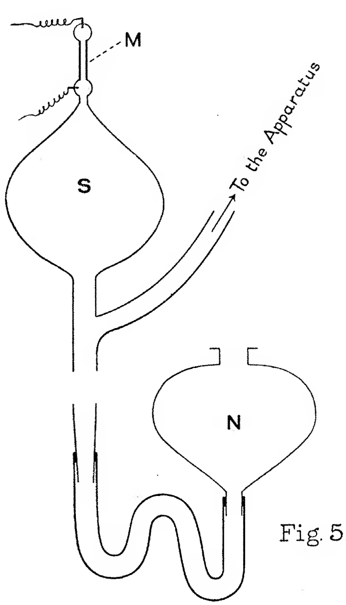


Fig. 5.

* J. Franck and G. Hertz, *loc. cit.*

was closed by a small capillary Geissler tube M. By means of the movable mercury reservoir N which was connected as is shown in fig. 5, the gas in the vessel S could be compressed to a small fraction of its initial volume. This was necessary, because at the pressures used in these experiments (0·01–0·001 mm.) a discharge sufficiently luminous to give a spectrum could not pass through the Geissler tube. The gas after standing for some hours in the apparatus in connection with a charcoal tube gave a strong spectrum of helium; the hydrogen lines were very faint.

The curves 1 (H_2) and 2 (He) of fig. 6 represent the results of the observations, the "extracting potential" being 8 volts in this case, ⊙ refers

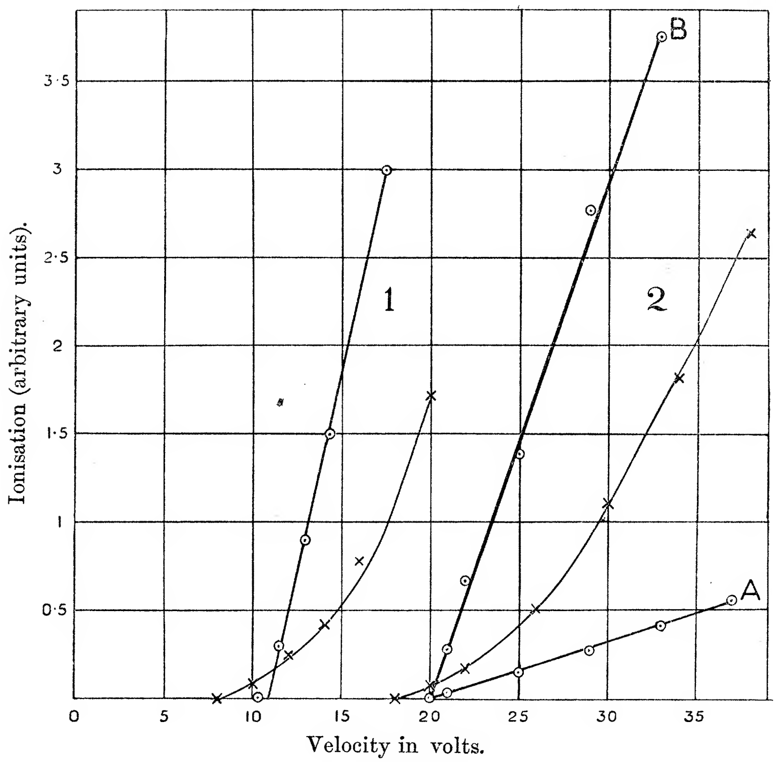


FIG. 6.

to negative corpuscles, × to positive ions. The main difference between the curves of the type ⊙ and the type × is clearly seen. For negative corpuscles they are very nearly straight lines, cutting the axis of x in definite points, corresponding to a velocity of 11 volts for H_2 and 20 volts for He. For positive ions they are curved lines, which in the present experiments also seem at first sight to cut the axis of x in a definite point, but probably only approach it. The difference becomes more obvious if one

increases the intensity of the thermionic current by increasing the heating current. In the case of negative corpuscles in He, on increasing the emission tenfold the straight line B was obtained, which cut the axis at the same point as A. This point was very sharply defined; for the velocity of 21 volts the ionisation was measured by the movement of the gold leaf of the electroscope, the rate being 50 divisions in 30 seconds, while for the velocity 20 volts the rate was only 50 divisions in 10 minutes. For the positive ions, as has been already mentioned, the effect of an increase of their number is, within the limits of the experiments, to shift the point of intersection of the curve with the axis of x towards the smaller values of velocities.

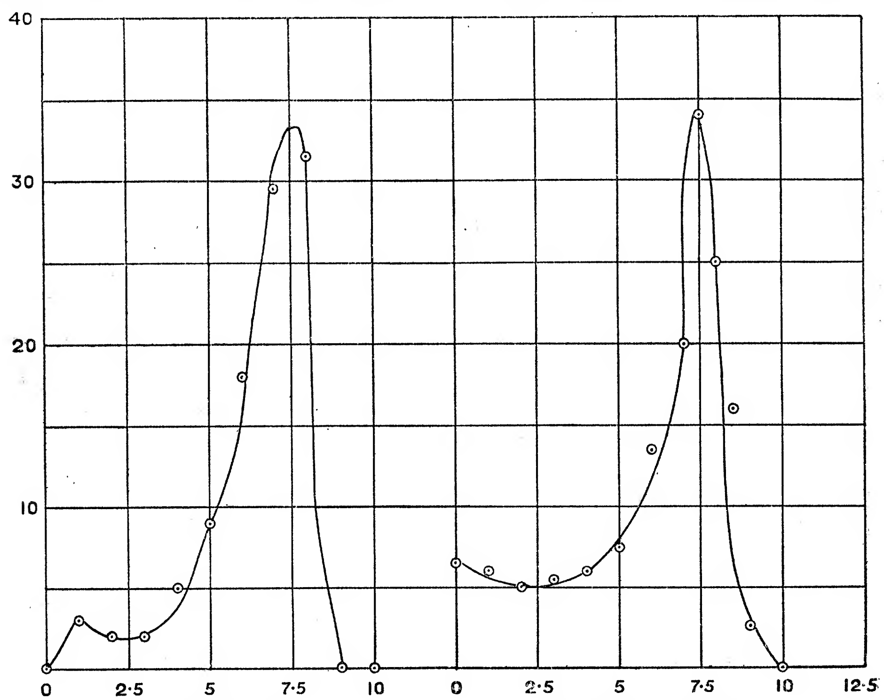
§ 4. *Distribution of Velocities.*

In order to be able to draw any definite conclusion as to the magnitude of the ionising potential, it was necessary to be sure that the actual distribution of electric force inside the apparatus corresponded to the potentials externally applied. In other words it was necessary to investigate the actual distribution of velocities among the negative corpuscles and positive ions. For this purpose an accelerating field was applied between the platinum strip P and the gauze R, and a retarding field between the latter and the bottom of the cylinder D. The cylinder itself was connected to earth through a sensitive d'Arsonval galvanometer, which gave 1 mm. deflection for a current 10^{-9} ampère. The current was measured with a constant accelerating potential difference between P and R, while the retarding potential between R and D was gradually changed from zero till it was sufficiently strong to stop the whole current. In the following an actual example is given:—The strip P was charged to $+10$ volts, the gauze R was earthed, and the current carried by the positive ions to the cylinder D was measured by the galvanometer. Then the strip was charged to $+9$ volts, the gauze to -1 volt, and the current measured again. In this case the accelerating field was still 10 volts, but all the ions having a velocity below 1 volt were now stopped by the retarding field of 1 volt, and the current in consequence became a little smaller. Proceeding in this way, and increasing the retarding potential by equal steps of 1 volt, we finally reach the stage when the current is reduced to zero. At one particular step the retarding potential produces a much greater diminution in the current than at any other. Since now the largest number of particles is stopped by this retarding potential, it is evident that the majority of the particles have a velocity slightly below that which corresponds to this value of retarding potential.

The Table contains the results obtained for both positive ions and negative corpuscles, with an accelerating field of 10 volts and 7·5 volts respectively.

Positive ions.			Negative corpuscles.		
Mean potential of the strip P.	Potential of the gauze R = retarding potential.	Current in percentage.	Mean potential of the strip P.	Potential of the gauze R = retarding potential.	Current in percentage.
+10	0	100	−7·5	0	100
+ 9	−1	100	−6·5	1	93·5
+ 8	−2	97	−5·5	2	87·5
+ 7	−3	95	−4·5	3	82·5
+ 6	−4	93	−3·5	4	77
+ 5	−5	88	−2·5	5	71
+ 4	−6	79	−1·5	6	63·5
+ 3	−7	61	−0·5	7	50
+ 2	−8	31·5	0	7·5	40
+ 1	−9	0	+0·5	8	23
			+1·5	8·5	10·5
			+2·5	9	2·6
			+3·5	10	0

Representing these numbers in the form of curves, and graphically differentiating them, it is quite easy to get the relative percentage of particles which corresponds to every velocity. This is represented on fig. 7A and fig. 7B, where the velocities in volts are taken as abscissæ and the



Positive ions.
FIG. 7A.

Negative corpuscles.
FIG. 7B.

relative percentage of particles as ordinates. It is seen that, in the case of negative corpuscles, we deal with a source of particles of nearly homogeneous velocity corresponding to the difference of potential actually applied. From this fact it follows that the intercept on the x-axis gives the absolute value of the ionising potential for negative corpuscles. In the case of the positive ions the results are slightly different. The maximum number of particles occurs at a velocity less than the velocity applied, and there are no particles at all which possess the value of the applied velocity. The distribution of velocities for positive ions was investigated at various pressures and with various applied velocities, less than 10 volts, but the same effect was always observed. Whatever may be the explanation of this fact, its influence on the value of the ionising potential for positive ions is only to make that potential still smaller than the value given by the curves.

§ 5. *Action of Magnetic Field.*

Finally, the action of a strong magnetic field on the positive emission and on the ionisation was studied. The experiments were carried out in the following order. The magnetic field might be applied between the strip P and the gauze D (fig. 1). At some definite velocity of the positive ions, for instance, 60 volts, the effect of the magnetic field on the magnitude of the thermionic current passing to the cylinder D was measured. In this particular case the positive thermionic current was reduced to 80 per cent. of its original value by putting the magnetic field on. In this case 20 per cent. of the positive ions were deflected from their path, so that they did not enter the cylinder D. On measuring the ionisation produced in the cylinder by positive ions of the same velocity, it was found that this also was reduced to about 80 per cent. of its value by applying a magnetic field of the same intensity. It is clear that, if 20 per cent. of the ionising agents are prevented by the magnetic field from entering the cylinder, the ionisation ought also to be 20 per cent. less. The intensity of the magnetic field was chosen so as to deflect completely the negative emission, and, under these conditions, no ionisation due to the negative corpuscles could be detected in the cylinder. These results may be taken as a fresh demonstration of the fact that there exists an intimate connection between the number of positive ions and the negative charge, observed in the ionisation chamber.

§ 6. *Discussion of Results.*

On examining the observations made and the results obtained we are led to the definite conclusion that the negative charge observed in the ionisation chamber depends only upon the presence in it of the positive ions and upon

their velocity. This power of the positive ions to produce a negative charge in the gas can only be explained in two ways. We may suppose that a process occurs analogous to that first observed by Wien* in the case of positive rays in a discharge tube, *i.e.* that a change takes place in the electrical state of the carriers themselves. The beam of positive ions may be in reality a mixture of positive, negative and neutral particles which are in a state of statistical equilibrium. The negative part is accelerated by the electric field inside the ionisation chamber, and the negative charge observed on the electroscope in this case would be carried by heavy negative ions. On the other view we have to admit the formation of new ions and corpuscles by the collision of the positive ions with molecules of the gas, *i.e.* we must admit ionisation by collision at such unusually low velocities as those used in these experiments. In this case the negative charge observed in the ionisation chamber is carried by corpuscles. The two points of view are not entirely different and it seems that the first hypothesis may possibly include the second. As the experiments of Sir J. J. Thomson† have shown, the passage of positive rays through a gas is always accompanied by a very strong ionisation of the gas in the tube. It seems quite reasonable then to treat this ionisation as a primary effect and to consider the neutralisation and the acquiring of a negative charge by a positive particle as a secondary effect.‡ On this view it is easier to understand how the positive particles could combine with the negative corpuscles, which are formed in the gas in the free state in the way explained. The charge actually observed on the electroscope would thus be the sum of the charges on both negative ions and negative corpuscles.

Accepting the second point of view, we see that our results remove some difficulties which arise in applying the theory of ionisation by collision to the results of Townsend's§ experiments. These experiments investigate the change, with the distance between the plates, of the current due to photo-electrons in the electric field and the conditions under which a spark is produced between the electrodes. The difficulty is that, expressing his observations by a theoretical formula

$$n = n_0 \frac{(\alpha-\beta)\, e^{(\alpha-\beta)l}}{\alpha-\beta e^{(\alpha-\beta)l}},$$

* W. Wien, 'Ann. der Phys.' (4), vol, 27, p. 1025 (1908).

† J. J. Thomson, 'Phil. Mag.' (6), vol. 24, p. 232 (1912).

‡ See, however, W. Wien, 'Ann. der Phys.' (4), vol. 39, p. 538 (1912).

§ J. S. Townsend, 'The Theory of Ionisation of Gases by Collision.'

where n is the number of negative ions which reach the positive electrode,
n_0 is the number of negative ions which start from the negative electrode,
l is the distance between the electrodes, and
α and β are the numbers of ions produced by negative and positive ions respectively in 1 cm. distance,

though we get complete agreement with the experimental results, we are led to conclude that positive ions possess the power of ionisation even in comparatively low electric fields and at comparatively high pressures. These last two conditions limit the energy acquired by the particles during their free path to a very small value, *i.e.* make the ionising potential for positive ions very small—a fact which was not observed in *direct* experiments. Now the result of the experiments described in this paper gives to this fact a direct experimental verification, proving that the energy required by a positive ion to ionise a molecule of a gas is of the same order as that required for this purpose by negative corpuscles. Now in some of the present experiments a negative thermionic current about 10 times smaller than the positive one gave an ionisation about 10 times larger with equal velocity of the carriers of electricity in both cases. The question thus arises: what is the cause of this difference between the ionising powers of negative corpuscles and positive ions? It seems possible to answer the question in this way. Within the range of velocities and pressures investigated here the collisions which result in the ionisation of a molecule of a gas occur much more often in the case of the negative corpuscles than in the case of positive ions. This view is confirmed by Townsend's* values for the numbers α and β of ions produced in 1 cm. distance by a negative corpuscle and by a positive ion. For helium he gives $\alpha = 0{\cdot}5$; $\beta = 0{\cdot}0095$, *i.e.*, in the case of negative corpuscles 50 per cent. of them make collisions which result in ionisation of the gas molecules, while in the case of positive ions only 1 per cent. of them succeed in producing ionisation.

§ 7. *Summary.*

1. The property of positive ions to produce a negative charge in a gas has been investigated for a considerable range of velocities of the ions.

2. It seems probable that the effect observed was due to ionisation by collision of positive ions.

3. The results show that the ionising potential for positive ions in hydrogen is about 10 volts, which is of the same order of magnitude as

* J. S. Townsend, *loc. cit.*, p. 49.

the ionising potential for negative corpuscles, the positive ions being derived from heated salts.

4. In a new experimental arrangement, measurements of the ionising potential for negative corpuscles were repeated, and the values, 11 volts for hydrogen and 20 volts for helium, were obtained, which confirm the results of Franck and Hertz.

5. Observations were made on positive ions emitted by heated sodium phosphate in hydrogen, oxygen, nitrogen, and helium.

Further experiments are in progress. When this research had been conducted to the point described above, a paper by E. v. Bahr and J. Franck appeared in the 'Verhandlungen der Deutschen Physikalischen Gesellschaft,' January, 1914, which contains results which are in agreement with those of the experiments described in § 2 of the present investigation.

The author gladly takes this opportunity of thanking Prof. Sir J. J. Thomson for his kind permission to carry on this research in the Cavendish Laboratory, and for the interest he has taken in the investigation.

The Determination of Fatigue Limits under Alternating Stress Conditions.

By C. E. Stromeyer.

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In the year 1867 A. Wöhler, locomotive superintendent of a railway company in Berlin, exhibited at the Paris Exhibition the results of some experiments on the endurance of metals, and was thereupon engaged by the Prussian Government to carry out the more exhaustive enquiry into this subject with which his name is always associated. The results of his labours were published in 1871, and were highly appreciated, but few additional experiments were made until the subject was again taken up successively by Sir Benjamin Baker, Reynolds and Smith, Rogers, Stanton and Bairstow, Eden, Rose and Cunningham, and Prof. Hopkinson. All these experiments are confined either to fatigue bending or to push and pull tests, using only steel or iron, whereas the present ones include a large number of torsion fatigue tests on various metals.